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14. ABSTRACT This report documents an AFOSR study performed by the UF GERC for a high speed diagnostic tool for chacaracterizing the behind-armor effects of various armor defeating munitions. Regions behnid the armor are continuously monitored with laser beams and photo-detectors so that passing fragments are detected when they temporarily shadow the detector outputs. During an event, all information is stored on a high speed, CCD detector based camera that is produced so as to store the high speed temporAL INFORMATION OF THE LASER BEAM BLOCKAGE. After the event, the camera data is digitized with a frame grabbing board and is subsequently digitally processed. (See attached "Abstract").

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Final Technical Report

Development of an all Electronic,
Behind the Armor Debris Witness Panel

Task Number 2304/KX

Contract No. F49620-98-1-0077

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ABSTRACT

This report documents an AFOSR study performed by the University of Florida Graduate Engineering & Research Center for a high speed diagnostic tool for characterizing the behind-armor effects of various armor defeating munitions. Regions behind the armor are continuously monitored with laser beams and photo-detectors so that passing fragments are detected when they temporarily shadow the detector outputs. During an event, all information is stored on a high speed, CCD detector based camera that is produced so as to store the high speed temporal information of the laser beam blockage. After the event, the camera data is digitized with a frame grabbing board and is subsequently digitally processed. Fragment movements are then tracked in software to provide a wealth of information such as particle size, velocity (direction and magnitude), and time of arrival. This information can then be manipulated in a number of methods to provide 1) raw data for input into hydrocodes, 2) comparison with x-ray film or witness panels, or 3) a simulated view of the time evolving spall pattern. During this research effort, an initial research system was developed and tested. Three primary testing events were performed including a flash exposure test, one-dimensional test, and then a limited two dimensional test. Data from each is presented in this report.

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3. Introduction

This report documents an AFOSR study performed by the University of Florida Graduate Engineering & Research Center for a high speed diagnostic tool for characterizing behind-armor effects. This research was conducted over a two year period. The first section of this report is dedicated to introducing the behind armor debris measurement problem, introduce traditional measurement techniques, and then to introduce the concept of the all optical technique used here. Next, we will discuss the design issues surrounding the instrument and will then conclude with a description of the experiments performed and their results.

4. Behind Armor Debris Background

Our application is for the analysis of behind-target-panel debris when targets are impacted by a munition [1,2]. Until now, flash X-ray and witness panels were the only practical tool to ascertain the number of fragments, their size, direction and velocity. Unfortunately, flash X-rays cannot record the low density materials that are now being used in aircraft, composite armors, and lethality enhancers for warheads. In addition, flash X-rays require large amounts of post processing to track the large number of fragments typically produced behind the armor impact point. Recently [3-7], holographic methods have been tested for application to behind armor debris measurement but as of yet, have not been adopted by the test community. One reason for this slow acceptance is the very large amount of data processing that must be performed to extract the behind armor debris from the captured holograms.

One of the large motivations for developing an accurate behind armor debris test tool is to allow comparison of actual data into hydrocodes which are currently being used to predict the performance of munitions impacting different materials. Currently, it is very difficult to capture all of the data necessary to test and verify these codes. Specifically, these users are interested in determining the mass and the velocity vectors of all fragments exiting the impact point Of lessor importance, but of potential future interest to code developers, is the actual time that the particle leaves the impact site. Of course all of these measurements have to be performed in very harsh environments with projectile speeds approaching 1500 m/s and with the number of significant projectiles being in the 100's to 1000's. ***Table I*** summarizes the requirements for a usable behind

armor debris collection system.

Table 1: Measurement Requirements

Requirement	Approximate Specification	Comments
Measure Particle Size	Particles typically < 3 mm are considered significant	Down to 1 mm is possible if necessary
Particle Velocity	up to 1500 m/s	Typically, velocities are 1/2 of impact velocity
Particle Direction	Need +/- 3 degree accuracy over a 45 degree spall cone.	
Material	Identify fragment type	Fragments are composed of the impacted material as well as penetrator material.
Particle count	Up to 1000 per event	Counting only the larger significant fragments

Figure 1 shows a simplified schematic of a test site. After the projectile is fired, extraneous components from the round, such as a sabot, are stripped with a series of concrete or steel stops. The projectile then flies to the impact site and strikes the material under test. It is after this impact point that the fragments must be measured. Given the very harsh environment, large amounts of shock, and the large amount of burning materials that are present after impact, careful selection of a spall measuring approach must be performed. In the remainder of this proposal, we detail existing/development approaches and then propose our method of developing an electronic witness panel.

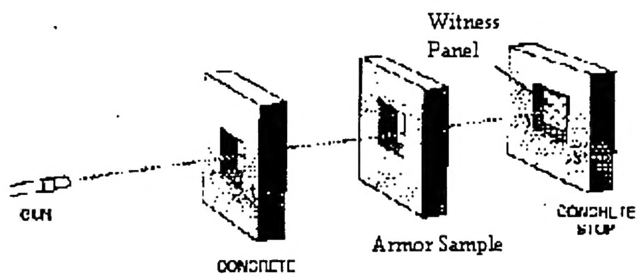

Figure 1 Schematic of Behind Armor Debris Test Range

5. Current Techniques for Measuring Behind Armor Debris

Over the past couple of decades, considerable amounts of work have been performed where it was necessary to measure the spall characteristics behind an impacted material. Unfortunately, the techniques to measure this information have advanced very little during this time period, in part due to the harsh environments in which the test events occur. In this portion of the proposal, we provide a brief introduction to the current techniques for measuring this information and summarize each of their strengths and weaknesses.

Witness Panels

For this technique, a series of plywood or Styrofoam sheets are placed after the impact point and along the flight line of the projectile. When fragmentation occurs, the projectiles impact the sheets leaving holes that can be analyzed to determine the direction that the projectile was traveling. Thus by finding the particle hole in two consecutive sheets, the direction of propagation becomes known. To extract the magnitude of the velocity vector and the particle size is more difficult. Usually, a series of panels is stacked with Styrofoam in between to gently stop the projectiles or fragments. Depending upon the number of sheets traversed by the fragment, an estimate as to its original velocity can be made. By recovering the projectile, its mass estimate is also found. Although the technique is simple in concept and very reliable, the man-power necessary to extract the information limits its true utility to support hydro-code development.

X-Ray Techniques

For this approach, orthogonal x-ray photographs are produced of the fragment field located behind the impacted material; i.e., the x-ray source is on one side of the fragment field and the recording film is on the other. Using two orthogonal sources, we obtain single image projections. Via a rather labor intensive effort, a user can determine the (x,y,z) components of each projectile. In addition, by viewing the two projections of the particle size, estimates of size can be made although this is not currently done. Once

again, extracting temporal and velocity information can be more difficult. On the same sheet of x-ray film, two pulse x-rays are recorded; one at time T_1 and the other at time T_2. If the user can then locate the same particle in the images at the two different times, the velocity vectors can be measured. The major difficulty with this approach is that for a large number of fragments, it becomes at best a very large effort to extract useful data.

Holographic Techniques

There are currently two optical holography techniques under development by the Instrumentation Group at Eglin's Wright Laboratories. The first of these is an internally developed approach [3-8] that uses cylindrical holograms to record ballistic events while the second uses a contractor developed holocamera to record the events. For brevity, we only describe the former.

Figure 2 shows the essential optical elements needed to produce the ballistic holograms. A 3 J, Lumonics ruby laser is the illumination source and can be operated in either single or double pulse mode. The laser pulse width is 18 ns resulting in peak output powers of 167 MW. For protection against flying fragments, the laser is located in a room adjacent to the ballistic tunnel. At the laser output, the beam is approximately 30 mm and is converted into a spherically diverging wave encompassing the hologram cylinder. A -75 mm focal length lens diverges the beam and is mounted on a metal stand located at the tunnel entrance. A disposable, 25 cm x 25 cm, mirror is used between the lens and the cylindrical film holder to fold the optical beam towards the gun barrel.

During a test event, film is loaded into the cylindrical film holder and the laser is charged. At a distance of 140 cm in front of the armor plate, an infra-red light source and detector senses the presence of the bullet and provides a laser trigger. The bullet pierces the armor creating the particle field and a large flash. The laser discharges capturing the fragment field in flight. If two time views of the fragment field are desired, the laser can be double pulsed while the fragments are still located within the cylinder. Pulse separations can be varied between 1 ms and 800 ms.

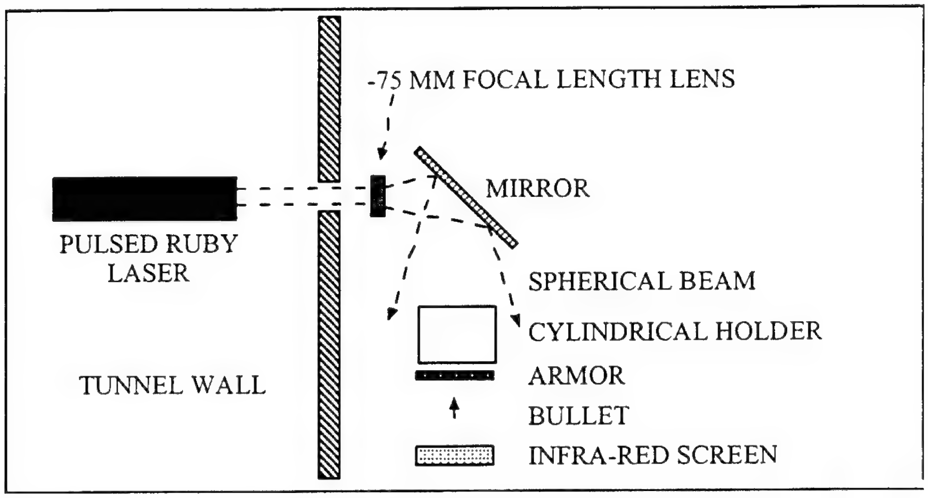

Figure 2 Cylindrical Holography Set-up

After the test event, the film is retrieved and loaded into a light tight film holder for transport to the darkroom where it is then developed. After the film is dry, it is viewed using a 20 mW helium-neon laser that is spherically expanded with a microscope objective. The 3-D hologram obtained from this technique can be rotated 180 degrees so that the user can effectively view the fragment field from any angle. If a 2-D picture is taken of the hologram output, outputs such as shown in ***Figure 3*** are obtained.

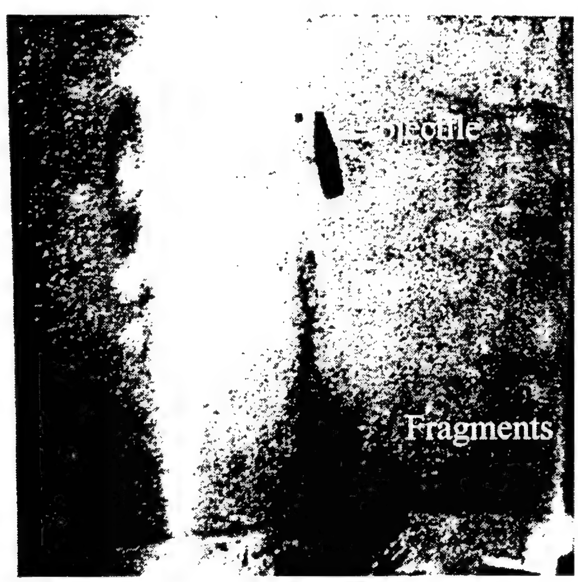

Figure 3 Behind Armor Debris Captured From Cylindrical Hologram

Although this technique has produced spectacular images, it has been slow to produce quantitative data for the reasons outlined below:

Flash - Behind the armor experiments produce a large amount of burning dust/debris that radiate tremendous amounts of light. Since this light is also recorded on film, care is necessary to insure that the desired laser light is much more significant than the ambient light during the event. For small scale events (20mm projectiles for example), this problem has been solved in cylindrical holography but for more realistic penetrators, this problem is unsolved. Wright Laboratories alternative holographic approach should solve this problem.

Numerical Complexity - For cylindrical holograms, the developed images are captured by a CCD camera having approximately 1000 x 1000 pixels (10^6). Typically, 20-30 camera images are captured from each hologram to feed into tomographic reconstruction algorithms for the fragment field. This results in approximately 3×10^7 pixels that must be processed.

Film Distortions and Noise - When holograms are recorded onto film, aberrations and noise occur in the reconstructed image for a number of reasons. Although these defects are tolerated by the eye, they have caused difficulty for the data recovery algorithms. To overcome, very specialized research will have to be performed in image processing.

Temporal Limitations - Most holograms are recorded with a single pulse (~18 ns long) of laser light thus freezing the particle field. In order to extract velocity vectors, two pulses, separated in time, have to be employed. Like the x-ray photographs, however, the user then has to find a method to track particles recorded in the first image to their new position in the second image. To date, little work has been performed in this area.

Comparison of Techniques

Table 2 provides a summary comparison of the existing techniques as discussed above. Due to the tremendous amount of data available from the approach, the holographic technique has the most potential for providing useful data for entry into the hydro-codes. Due to the uphill battle yet faced to extract data and to then extract temporal information, it is not yet clear that holography will provide the final solution.

Table 2: Summary of Techniques

Technique	Strengths	Weaknesses	Description
Witness Panels	Simple, reliable, and low cost.	No time history, limited velocity information, very personnel intensive to evaluate results.	Plywood or foam panel show impact points.
X-Ray Photography	Reliable technique, Provides reasonable images, low cost	Very difficult to extract velocity vectors in dense fragment environments. Labor intensive.	Flash X-ray captures orthogonal views at two time instances.
Holographic	Tremendous spatial fidelity for fragments. Provides excellent visual affects.	Difficult to extract velocity/timing information. Unproven, computation intensive algorithms required to extract data.	Hologram of fragment field is made so that 3-D image can be constructed post event.
Stereo	Can be time-resolved thus allowing velocity/timing information to be extracted	Costly and algorithms for tracking/characterizing debris fields only partly developed	Two cameras, at different angles, are used to view debris field.

6. An All Electronic Behind Armor Debris Witness Panel

Referring back to ***Figure 1,*** suppose that an all electronic witness panel could be constructed that would record the size and (x,y) coordinates of each projectile as it passed through the clear aperture of the panel. That is for each projectile, the coordinates (x_1,y_1,z_1,t_1,s_1) would be known if the z-position of the screen is known, the time stamping of the screen was very rapid, and an estimate of the size (s_1) could be determined. Now suppose that at a known distance down range, maybe 50 mm, a second witness panel is placed where another set of coordinates (x_2,y_2,z_2,t_2,s_2) is recorded for the incoming particles. If this data was available from every particle, it would be possible to calculate velocity vectors, timing, and estimate fragment size. All of this data could be provided to the hydro-code users.

Given the very harsh environments and the rapid time scales of the events of interest, a number of questions come to mind. These are 1) how can we build such a witness panel that measures this information for clouds of fragments traveling Mach 3 or more, 2) is component technology available now to support such a device, 3) are the data extraction algorithms going to be as complex as for other techniques, and 4) has there been any work done in the area that might minimize the risk. In this section, we attempt to answer those questions.

Concept

Figure 5 illustrates the concept of the optical witness panel. In operation, two laser diodes are used to create two fan optical beams that intersect at ninety degree angles. As shown, the intersection of these fan beams covers a 4' x 4' target area; larger areas are possible as well. For starters, let's assume that only one projectile is present in the fan beam at a time (more realistic complexity is discussed later). As shown in ***Figure 6,*** suppose on the far side of the fan beam, a large array of very fast optical detectors is placed. As illustrated, the moving particle will temporarily cast a shadow onto those detectors who can then rapidly record the absence of laser light. In the orthogonal direction, a shadow is also produced on its corresponding detector array. Notice that for each laser/detector array pair, we can measure one angular coordinate. With both laser

transmitter/receivers operating, we can record the two orthogonal angles for the particle after which it is straight forward to determine (x_1, y_1, z_1); note, that we know z_1 because of the screen placement. In addition, note that the size of the shadow cast has a direct correlation with the projection of the particle size. When the projection measurement is performed in two axes, an estimate of particle size is available. Finally, the timing of the shadow (assuming very fast detectors) tells us all of the desired measurements for panel 1: (x_1,y_1,z_1,t_1,s_1). By placing a second pair of laser transmitters/receivers a small distance down range, we can measure (x_2,y_2,z_{12},t_2,s_2).

In practice, a large number of detectors is needed to provide sufficient accuracy. For example, suppose 512 detectors were used on each side of a 4 ft by 4 ft test region. The resulting spatial accuracy would be approximately +/- 1 mm which is on the order of that required for spall measurement Suppose now that the projectiles are traveling at 1500 m/s or less. If we require that we interrogate the detectors before the projectile moves more than 3 mm as an example, then the detectors have to sample every 2 μs. To build up such a large array of fast detectors from scratch is quite impractical. Fortunately, a slight modification can be made to allow the use of a commercially available detector arrays to accomplish the exact same function.

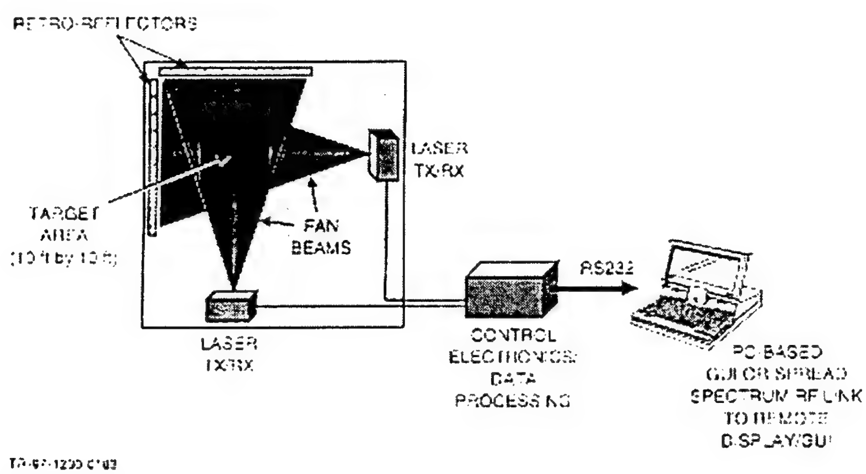

Figure 3-1. Small Arms Target Scoring System

Figure 4 Witness Panel

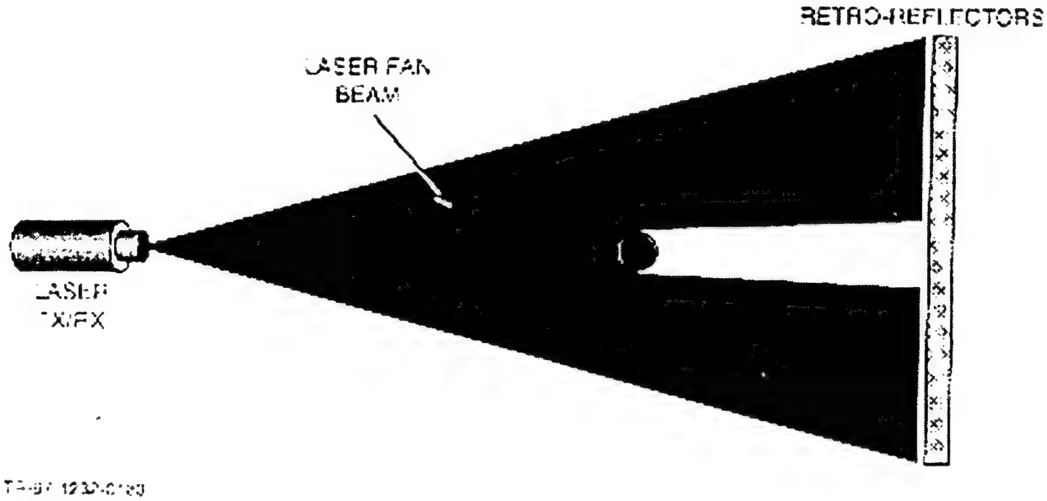

Figure 3-3. Laser Fan Beam and Retro-Reflective ("Shadow Hunter") Concept

Figure 5 Fan Beam With Detectors

As an alternative, suppose that each laser fan beam propagates through the test region to a strip of retro-reflective tape. This low cost tape returns the optical beam along the same path as the outgoing beam; i.e., the laser beam retraces its path through the test region and to the laser transceiver. This concept is illustrated in ***Figure 5***. In each transceiver, a detector array (i.e. CCD) is utilized to measure the light. When no projectiles are present, all elements of the detector array are fully illuminated with the reflected laser beam, and no action is required. When a projectile is present, a portion of the optical fan beam will be blocked, thus making one or more detectors receive no light. This absence of light is to be detected in the CCD output. By noting which detector(s) are dark, it is straight forward to determine where the projectile is located, in angle, relative to the laser transceiver. At the same time, the orthogonal laser transceiver also registers a dark output and hence measures an angular coordinate in the orthogonal direction. ***Figure** 7* illustrates the linear CCD output with a projectile breaking both laser beams. By making these measurement devices orthogonal, we can readily determine the x, y coordinates from the measures angular coordinates.

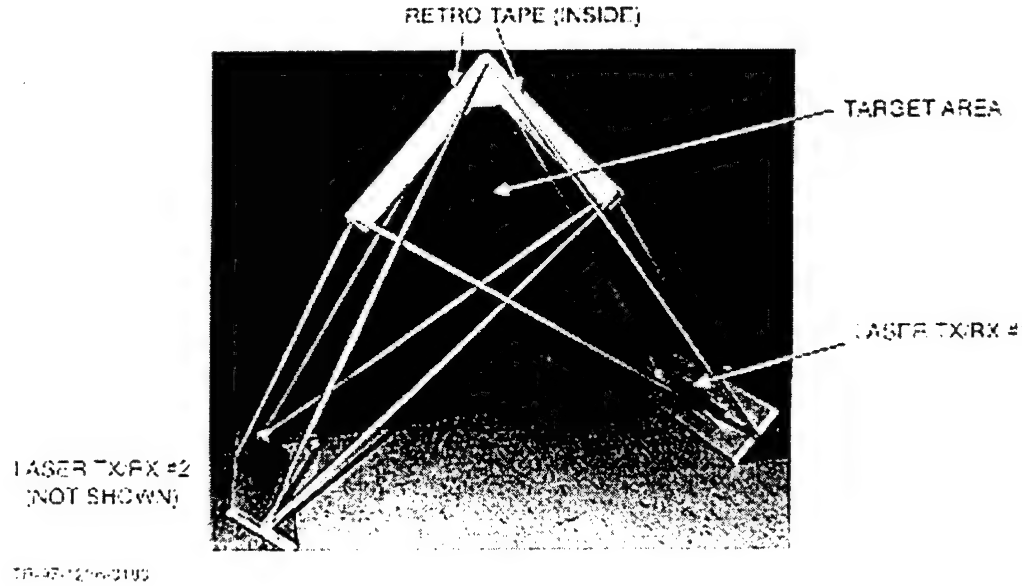

Figure 13-1. Phase I Breadboard SATSS Structure

Figure 6 Retro-Tape Based Approach

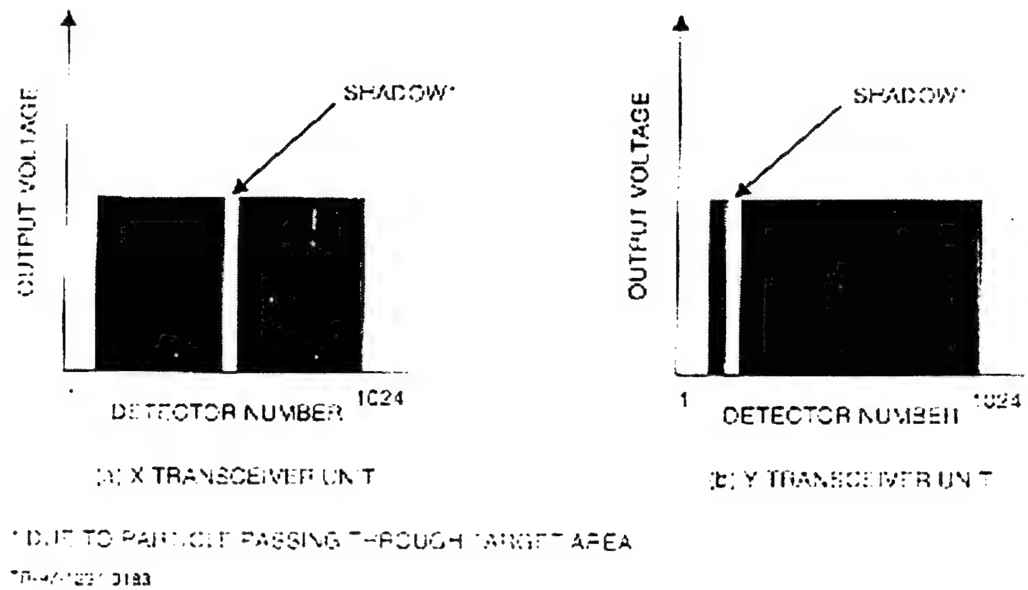

Figure 3-2. An Example Detector Output From SATSS Transceivers

Figure 7 Example CCD Detector Output

Extension to Multiple Particles

The above concept can be readily extended to the practical situation of hundreds or more fragments being produced during an impact event. To sort out this complex fragment pattern, we need to take advantage of the temporal collection properties of the witness panel. Suppose that on a much slower time scale, we could watch the particles break the laser beam as they pass. At the beginning of the event, the laser beam will be broken initially by one particle. The data from this time instant is saved and from it, we can extract the position information as described above. Now suppose in the next time instant, the first particle continues to break the laser beam but another particle also breaks the beam. Since we already know the shadow position from the first particle, the shadow positions from the second can be readily found; note that all of this sorting is performed on the data after the test is complete. In this manner, we could track a large number of fragments during an event if they all arrived at different times. Even though many fragments may be blocking the beam simultaneously, if they all arrived at different times, it is straight forward to separate the shadows from each.

In practice, we know that some projectiles will first arrive in the beam at the same time. In this case, we must determine which shadows correspond to each fragment. A number of possibilities exist. First, if the size of the fragments are markedly different, it will be easy to determine which shadows come from the big particle and which come from the small particle. If the particle sizes are similar, we can wait until they cross the second optical beam at which point they may arrive at different times. In many cases, we will be able to back track and determine the original position in the first optical beam. Finally, it is possible to resolve this problem by putting in the two optical screens with a tilt relative to one another. All these possibilities must be explored.

Collection of High Speed Data

A practical issue still exists since linear CCD cameras are readily available with enough detectors (up to 6000) but they do not operate at speeds fast enough to accurately capture multiple time samples. For example, suppose we want to interrogate the line of detectors every 2 μs over a time period of 0.5 ms. This requires that the data from the linear array be read out and stored every 2 μs for a total of 250 times. This readout rate is

well above what is commercially available.

To solve this problem we propose to use a two dimensional CCD camera, having at least 512 x 256 pixels, to solve this storage problem. As illustrated in ***Figure 9***, the retro-tape is imaged onto a single vertical array of pixels. These detectors store electrons proportional to the number of photons integrated during the exposure time. After this exposure, the charge is moved to the next array of detectors and the detectors in the illumination area are ready to collect light again. This process continues until a total of 256 lines of data are collected after which the detector outputs are digitized and read into a computer using commercially available frame grabbing equipment. Thus as we look across the array output, we see that in the vertical direction is the instantaneous light intensity and in the horizontal direction corresponds to time. The attractiveness of the approach is that the scanning operations described are non-mechanical and they already occur in commercially available cameras.

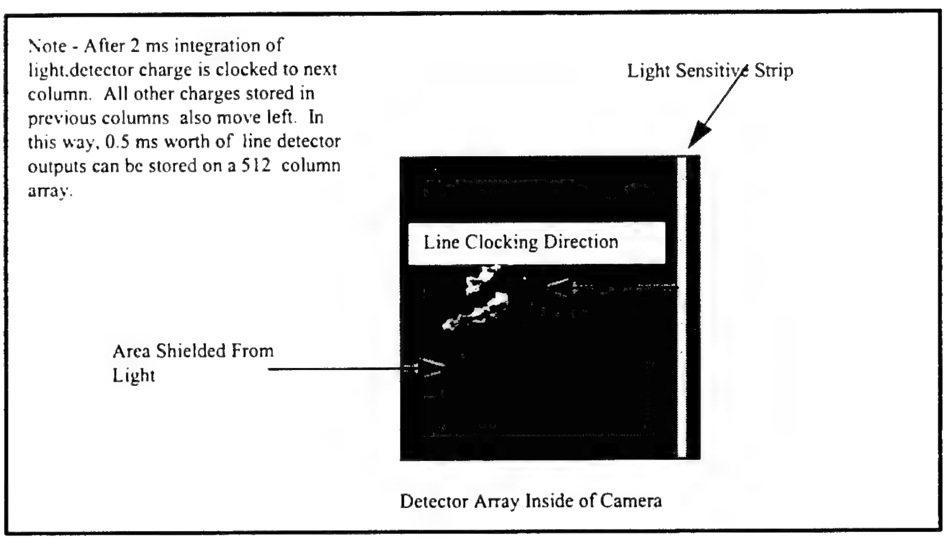

Figure 8 Use of 2D CCD to Store Time Information

3Introduction to Data Extraction Algorithms

Figure 9 shows a potential output from one two-dimensional CCD camera. Although this is not a densely populated example, it illustrates the algorithmic approach that will be taken. These algorithms are implemented after event completion and thus do not have to be accomplished in real-time. Currently, a total processing time of around 5

minutes is estimated as the longest that it would take to extract all information. Starting a time 0 and going out to 0.5 ms, we see the idealized output of the detector array. The first projectile begins to break the beam at some time T_1. Since there is only on particle present **(at this time point)**, we can find the corresponding shadow on the orthogonal camera. and then determine all coordinates for this particle (x_1,y_1,z_1,t_1,s_1). While this particle is still present, a second particle breaks the first screen thus leaving two shadows. Since we already know the shadow locations for the first particle, it is straightforward to determine the shadows corresponding to the second particle. If no two particles break the beam at the same time, this process will result in a unique solution for all particles on this first screen. Conceptually, and in practice, these algorithms are much simpler to perform than the tomographic reconstruction required for holography.

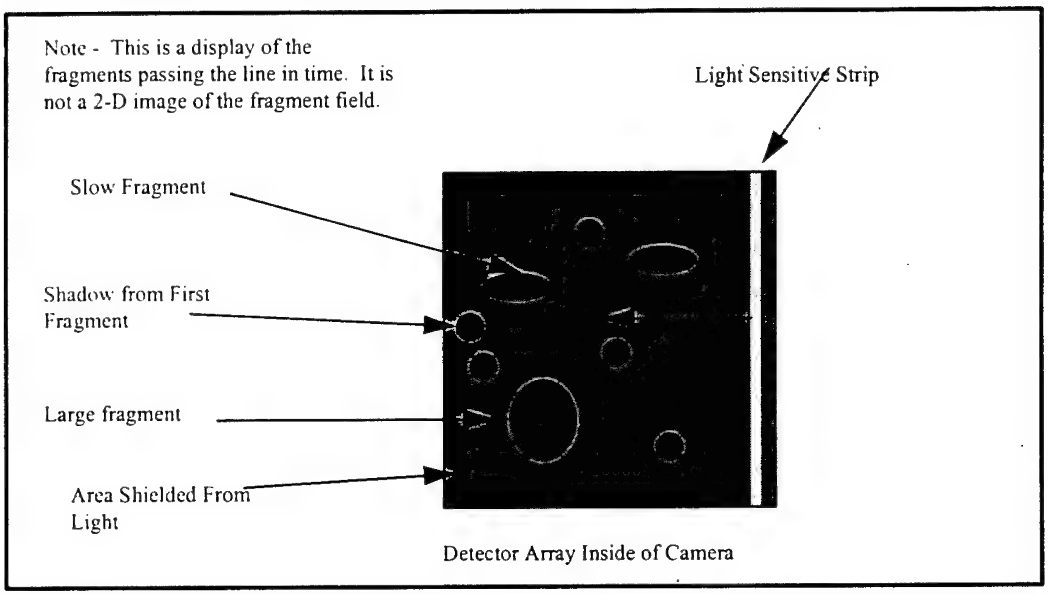

Figure 9 Example CCD Output

Survival in Harsh Environments

One question of any optical approach is will it operate and survive in the harsh behind armor debris environment. The two major problems for the optical systems is the large amount of light generated at the impact site and damage by fragments. The former is relatively straight forward to solve for this approach since 1) laser illumination is used in convenient geometry so the narrow line width optical filters can be used, 2) the time

the detector is exposed to the flash is very short (2 μs) as compared to 5-10 ms for holographic approaches, and 3) each detector only observes a small region of space behind the armor. Early tests will be performed to verify the ability to operate in the high flash environment. Fragments are not anticipated to be a problem since the frame size can be scaled to ensure that the important devices are always outside the spall cone. In addition, armor could be placed around the front and back of the screen to provide further protection.

7. Research

Detailed in this section is the research that was performed during this research effort. As was proposed, a step-by-step method was used to minimize risk and provide the maximum opportunity to learn via frequent tests/experiments and then be able to adjust. Specifically, our goal was to 1) measure the flash of big behind armor events by piggybacking onto a test at Eglin, 2) build a 1-D system that is tested first on small scale events followed by large scale events, 3) develop a full 2-D system that is tested again with small scale first followed by larger scale, and 4) demonstrate data extraction algorithms at several points throughout the program. While some of these activities were hampered by practical issues encountered along the way, the research went mostly as planned.

Initial Test

The initial tests of the concept were performed at the Advanced Warhead Experimentation Facility (AWEF) located at Eglin AFB. This was a piggyback test of a shaped warhead experiment that was being performed by Dr. David Lambert of AFRL. Do to the sensitivity of the tests, limited pictures are provided.

The primary purpose of this test was to determine if 1) the flash environment would make the shadow hunting technique too difficult to perform or if 2) the dust created would greatly interfere with the tracking of large projectiles. For this test, we instrumented the site immediately behind the impact point of the warhead into an armor plate. On one side of the shot line was located a 1 mW, collimated laser diode and on the other side was a tri-head, optical collection unit. One of the photodetector receivers was optically filtered and used to monitor the laser signal and the other two were used to measure optical power: one for the 600-700 nm optical band and the other for the 750-850 nm band. Figure ? shows a picture of the optical collection head. In addition to this instrumentation, the event was also viewed with a high speed Hadland, digital camera.

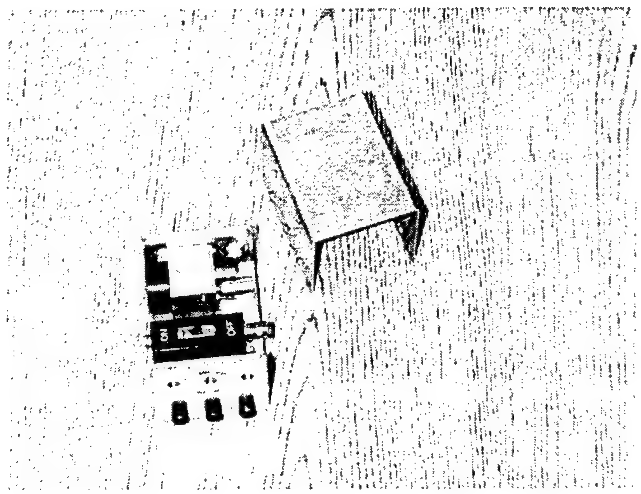

Figure 10 Photo-receiver For First Test

Figure ? below shows one the traces obtained from which several features are obvious. First, the large amount of flash played little role going through the 3nm wide optical filter (center 670 nm). Second, we could clearly locate 2 fragment events (only a small pencil beam was used), and third, the dust does not play a large role in the output signal and can be easily removed. From a total of 5 tests that were performed, it was concluded that the fragments could be observed as expected.

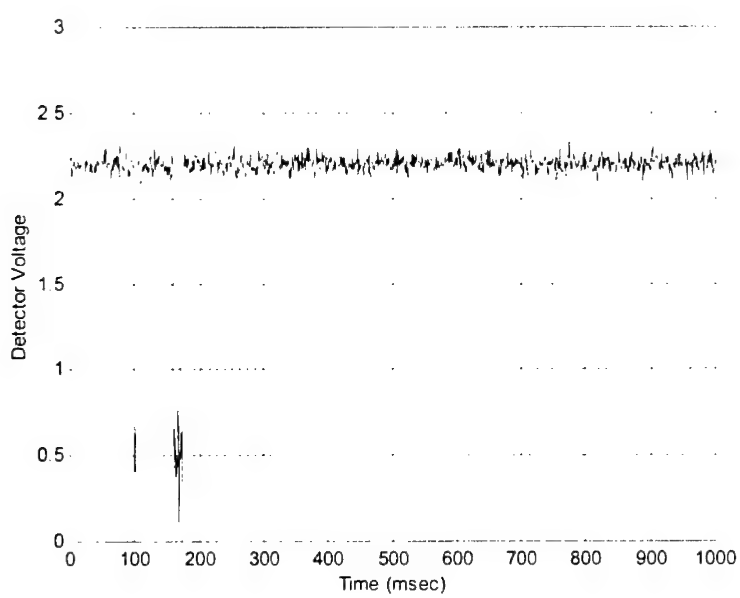

Figure 11 Laser Detector Plot Showing Fragments

Design Activities

After conclusion of the first tests, one of the major efforts of the research project was performed in designing custom optics for the various test phases performed. Some of the more stressing requirements including operating over very large field of views, small objects to resolve, and a requirement for large depth of field.

To create and image the entire fan field, an overall optical system layout looks like is shown in Figure 12. Notice that on a relative scale, the optical imaging system is quite small to the total test facility. Figure 13 shows a close-up of the final optimized lens design used to this work. Ultimately, a 5 element design was performed and implemented using ZEEMAX design software. The remaining figures show the ray fan and spot diagram plots for both on axis and off axis rays. This level of performance was deemed suitable.

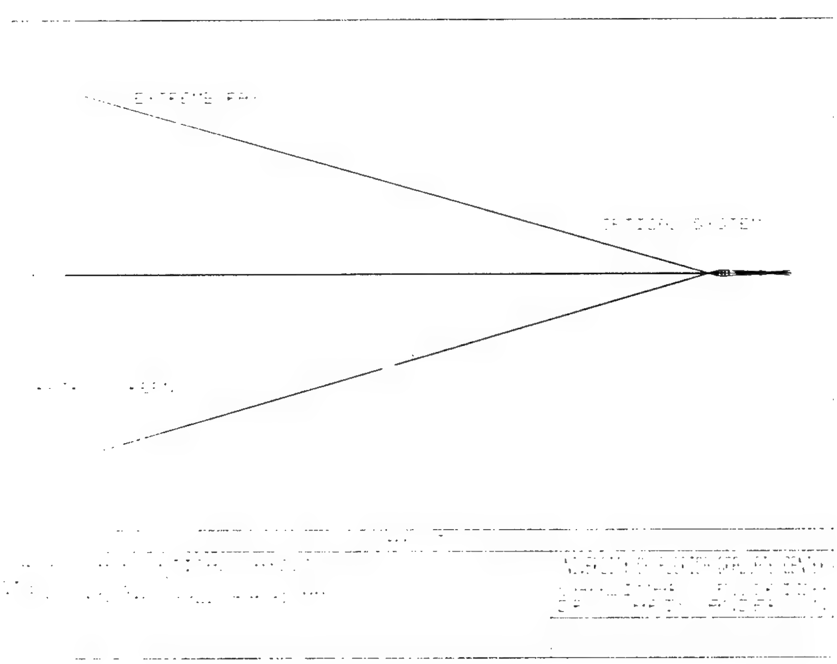

Figure 12 Overview Of Fan View Optical System

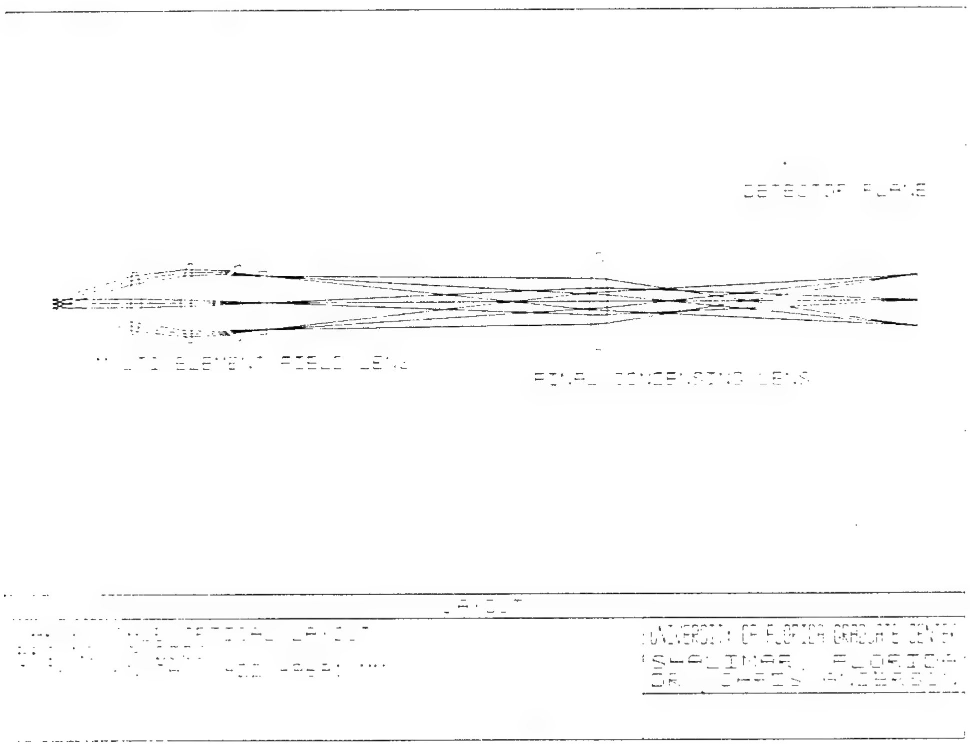

Figure 13 Close-Up Of Fan Imaging Lens

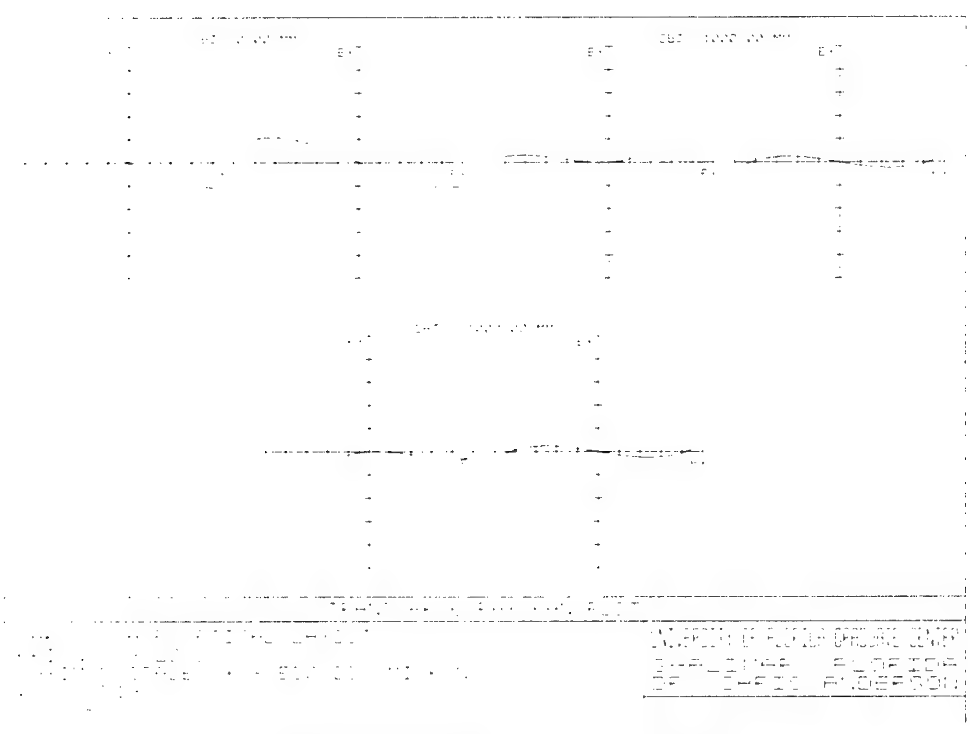

Figure 14 On And Off Axis Ray Fans For Imaging Lens

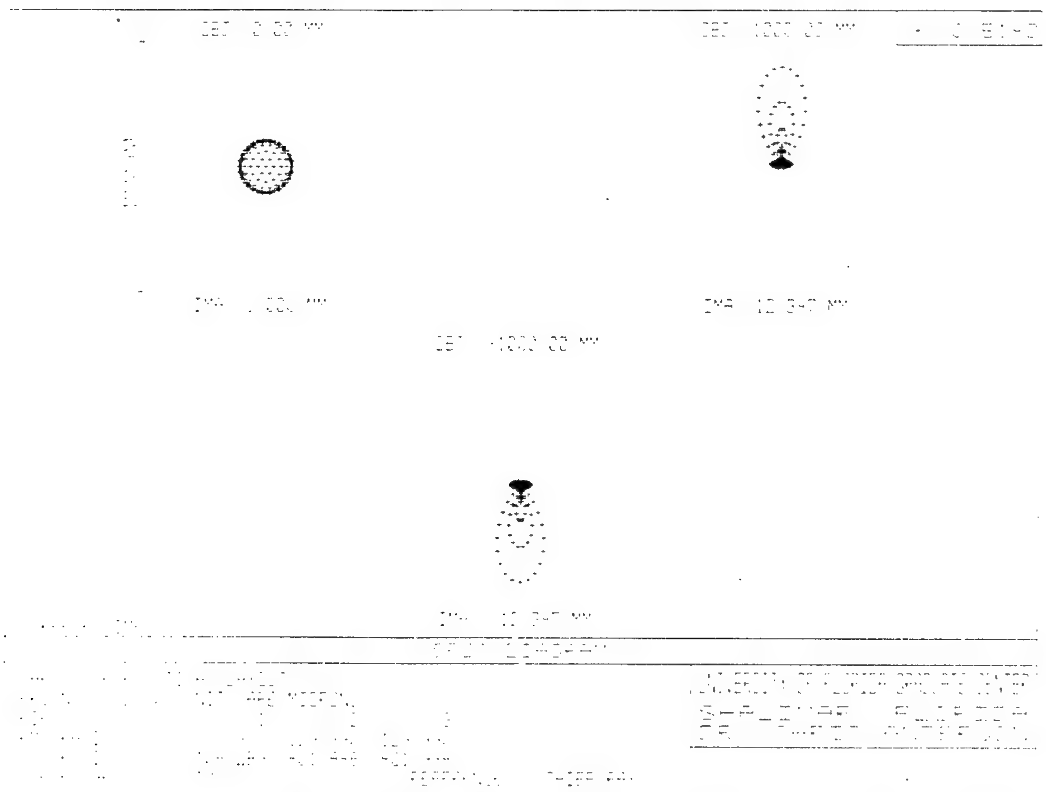

Figure 15 On And Off Axis Spot Diagrams

Camera Selection

Locating the proper camera for this application was one of the most difficult aspects of this research project. And EG&G Reticon line scan camera was selected and is shown in the picture below. Specific requirements on the camera are listed below as well.

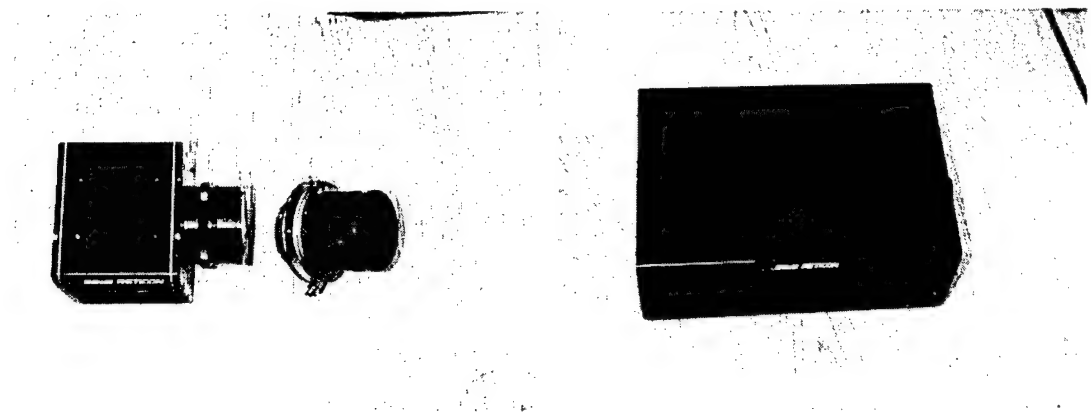

Figure 16 Reticon Camera And Power Supply

- 16 μm pixel size
- Minimum 768 x 512
- Prefer 1317 x 1035 Image Only On One Line But Line Is Clocked Orthogonally to build up a time
- history
- < 3 μs line clocking time
- External Start triggered event with less than 10 μs start time uncertainty; i.e., after
- the trigger, the camera clocks the line images until the entire array is used.
- Time Between Trigger Arming and Trigger Event > 5 minutes
- Camera clocks until all lines are filled and then stops
- Final data can is then extracted into PC computer
- Camera to computer distance > 10 ft

Image Acquisition Boards .

For this application, the major requirement of the frame grabber boards was to 1) be triggerable and to 2) be compatible with the chosen line scan cameras. In addition, we desired that the boards be compatible with Labview since this was the chosen software for this project. Figure 17 shows a picture of the frame grabber board.

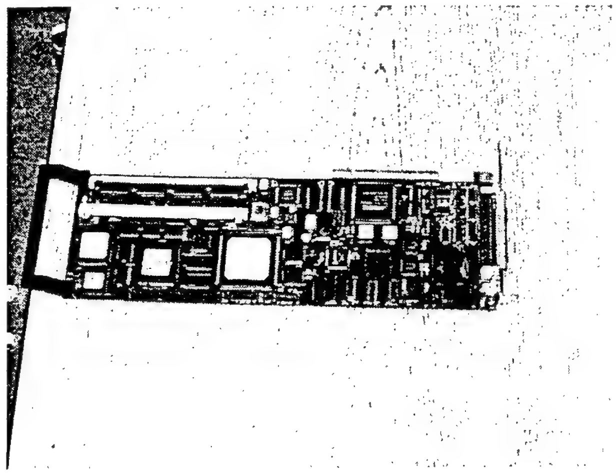

Figure 17 National Instruments Frame Grabber Board

Processing Software

For this project, we selected Labview as the primary processing software since it can interface and control the cameras, allow complex timing of multiple events, and has a user friendly, graphical user interface. The screen shot below shows one of the early screens used for camera control and initial data observation.

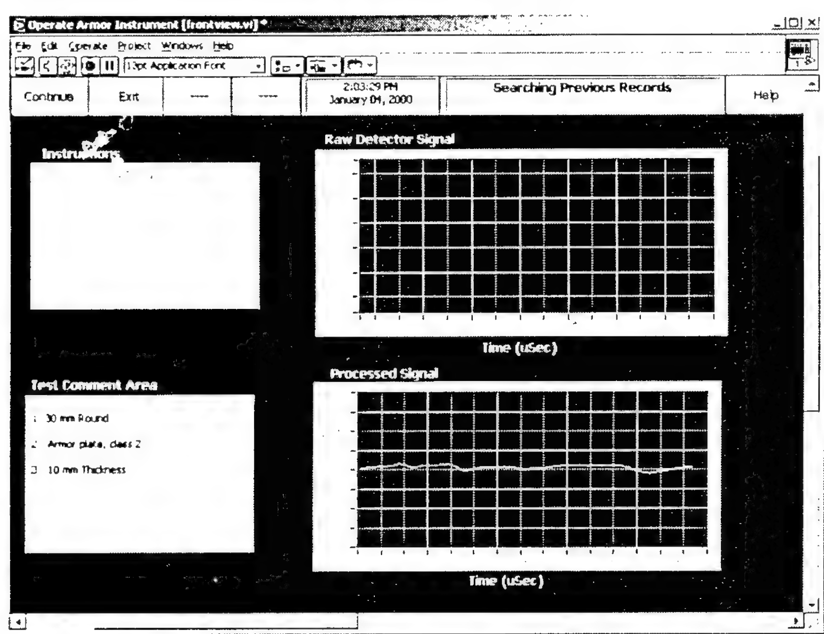

Figure 18 Screen Shot Of Image Capture/Processing System

One Axis Tests

Once the optical system was constructed, a series of tests were performed in Bay 10, located at Eglin AFB. The objective of this series of tests was to perform testing of the full concept and to begin initial development of the controlling software. In addition, initial mechanical structures were developed to house the optical set-up. Figure 19 shows a picture of one of the armor plates that was impacted during the tests. In all cases, 20 mm rounds were fired into 0.25" thickness armor plate. Figure 20 shows a picture of the gun launch located 20 meters uprange.

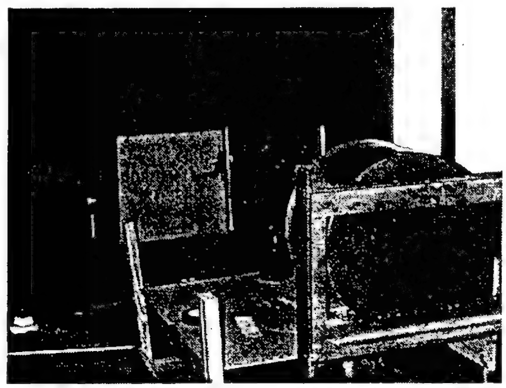

Figure 19 Impacted Armor Plate

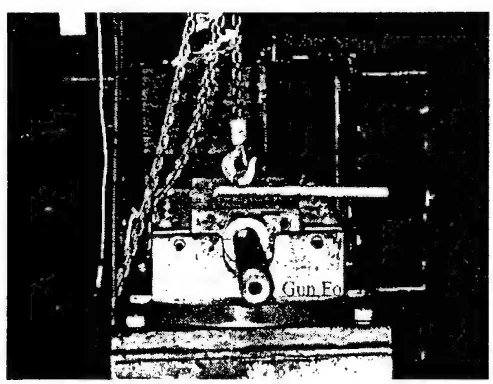

Figure 20 Gun Barrel

Figure 21 shows some of the raw imagery that results from performing these tests. As the pictures illustrate, unexpected amounts of noise were present in the image, in large

part due to slightly insufficient laser power. It was estimated that the SNR was approximately 15 dB. Interpretation of the images is as follows:

- Horizontal axis corresponds to time steps in 20 microsecond steps.
- Vertical axis corresponds to angle from the sensor with 129 being along the optical axis.
- Dark areas, corresponding to blocking fragments, appear for short periods and then disappear after no longer being located in the fan beam.
- The size of the vertical axis is indication of fragment size in the cross fan beam direction.

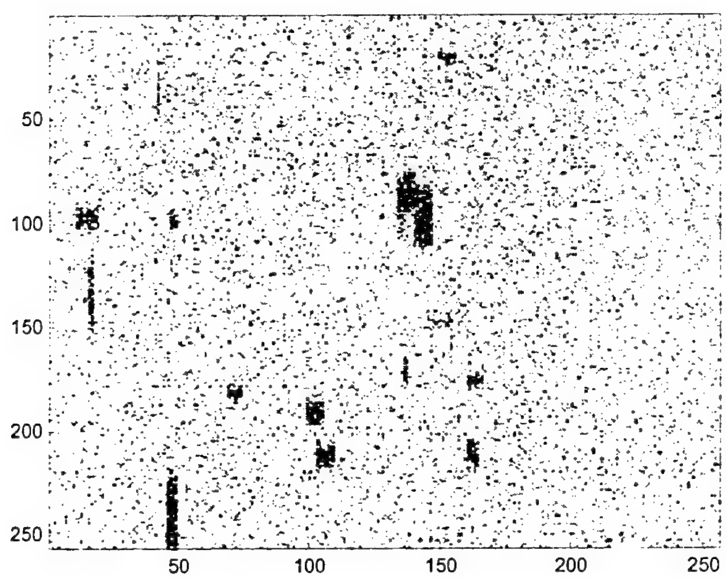

Figure 21 One Dimension Test Results

With a low fragment count, such as illustrated in Figure 21, it is reasonably straight forward to track fragment start time, size, and location. Automating this data extraction, however, proved difficult due to the low SNR environment. In some of the test events, a large number of fragments was observed such as illustrated in Figure 22. In this case, with low SNR it became difficult to separate fragments.

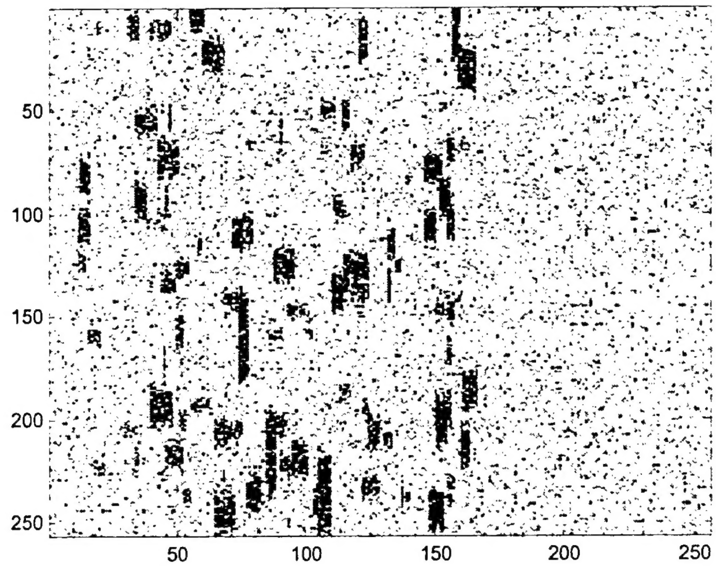

Figure 22 One-D Test With Many Fragments

Two Dimensional Testing

These tests were also produced in Bay 10, again using 20 mm rounds and armor plates. Figure 23 shows an example the horizontal (H) and the vertical(V) camera outputs side by side. Since the vertical and horizontal beams are aligned in the same plane, you expect that optical beam breakage occurs nearly simultaneous for both orthogonal channels. Starting at initial time zero, a manual determination could be made as to the two orthogonal angles of the fragment. Next, the second time slice was analyzed and so on. Unfortunately, because of the low SNR, we found that automating this process was not possible. Like the one-dimensional case, manual interpretation becomes difficult when large numbers of fragments are present at nearly the same time.

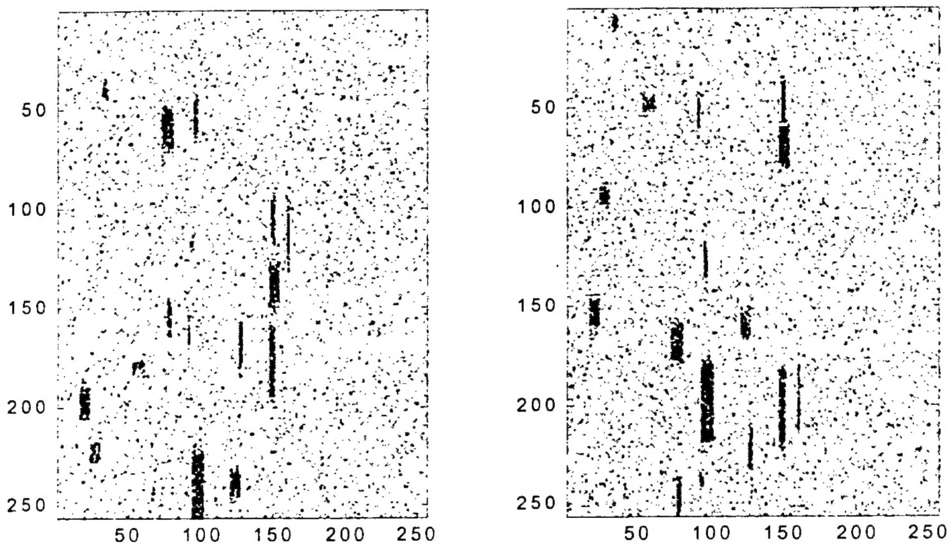

Figure 23 H/V Plot, Low Fragment Count

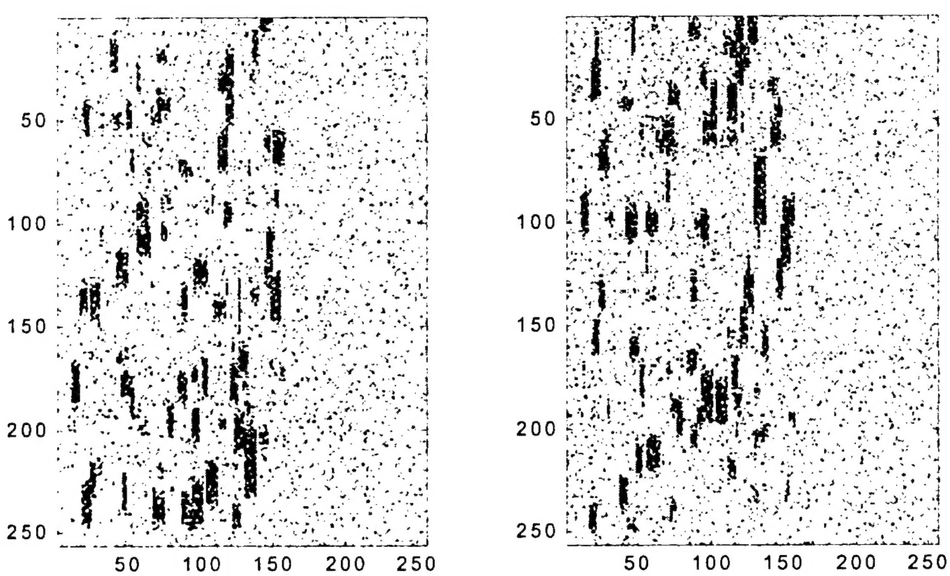

Figure 24 H/V Plot With Large Number Of Fragments

8. Discussion And Recommendations

As the imagery shows from both the one-dimensional and two-dimensional cases demonstrate, fragment imagery can be obtained in a ballistic environment. This is also true in large flash environments that were encountered. The major difficulty that we faced in this task was low SNR from the cameras. After considerable effort tracking the problem, we determined that the primary culprit was our inability to afford to produce the high quality optics need to preserve spot size on the cameras. In this project, we completed a design for an optical system that would be suitable however at $15,000 per copy, it was beyond the scope of what we could afford.

At this point, specific recommendations are listed below:

- Continue pursuing this approach since the imagery demonstrated feasibility;
- Invest in producing the optics designed during this project in order to improve performance;
- Investigate the moderate cost,high-speed 2-D cameras that are coming on-line for possible application.
- Once these efforts are performed, then automatic tracking software for the fragments should be possible.

With these efforts we believe that small scale fragmentation tracking can be readily performed.

9. References

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